EVALUATION OF BREAKWATERS AND SEDIMENTATION AT DANA POINT HARBOR, CA

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Abstract: A flow, wave, and sediment transport model, the Coastal Modeling System (CMS), was applied to evaluate current and sedimentation patterns at Dana Point Harbor on the southern California coast. The permeability of breakwaters is the main interest in the study for the structural integrity and functioning to protect the harbor. Two Acoustic Doppler Current Profilers (ADCP) were deployed in November 2009 to collect current, water level, and wave data inside and outside the harbor. The model was validated by the field measurements. Wave transmission, flow penetration, and sediment seepage through the breakwaters were verified by the historical dredging information.

Introduction

Rubble-mound coastal structures, such as breakwaters and jetties, and groins, are built to protect coastal development from waves and tidal action. Because typically comprising of irregular, rough stones or concrete armor units, rubble mound structures usually contain voids among individual stone or armor units. As a result, the voids allow absorption and dissipation of wave and tidal current energy but also provide pathways for flow and sediment moving through structures. In numerical modeling, rubble mound structures are often treated as solid and impermeable walls. However, depending on the design of and the armor units used for rubble mound structures, the volume of water and quantity of sediment transport through breakwaters, jetties, and groins can be substantial to alter flow pattern, increase sediment deposition, and induce significant beach erosion and shoreline change in protected areas (TM 5-622/MO-104/AFM 91-34 1978).

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14. ABSTRACT
A flow, wave, and sediment transport model, the Coastal Modeling System (CMS), was applied to evaluate current and sedimentation patterns at Dana Point Harbor on the southern California coast. The permeability of breakwaters is the main interest in the study for the structural integrity and functioning to protect the harbor. Two Acoustic Doppler Current Profilers (ADCP) were deployed in November 2009 to collect current, water level, and wave data inside and outside the harbor. The model was validated by the field measurements. Wave transmission, flow penetration, and sediment seepage through the breakwaters were verified by the historical dredging information.

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In coastal applications, it is important for hydrodynamic and sediment transport models to simulate wave transmission and flow penetration through rubble mound structures (d'Angremond et al. 1996; Garcia et al. 2004; Tsai et al. 2006). The present study applies the methodology simulating the permeability of rubble mound structures (Reed 2010) in the CMS to Dana Point Harbor on the southern California coast. The hydrodynamic calibration and sediment transport validation are conducted against the field measurements.

Study area and data collections

Dana Point Harbor is located in Orange County on the US Pacific coast, 40 miles southeast of Los Angeles, CA. The harbor is entirely manmade and is protected from ocean waves by a pair of riprapped breakwaters constructed in the late 1960s. The breakwaters, consist of a long shore-parallel West Breakwater of 5,500 ft and a shore-normal East Breakwater of 2,250 ft (Figure 1), were designed as permeable structures. As these structures can dissipate wave energy and reduce wave reflection, the current and sediment transport can pass through. As a result, fine sands are accumulated inside the West Breakwater and maintenance dredging is required periodically (County of Orange 2009).

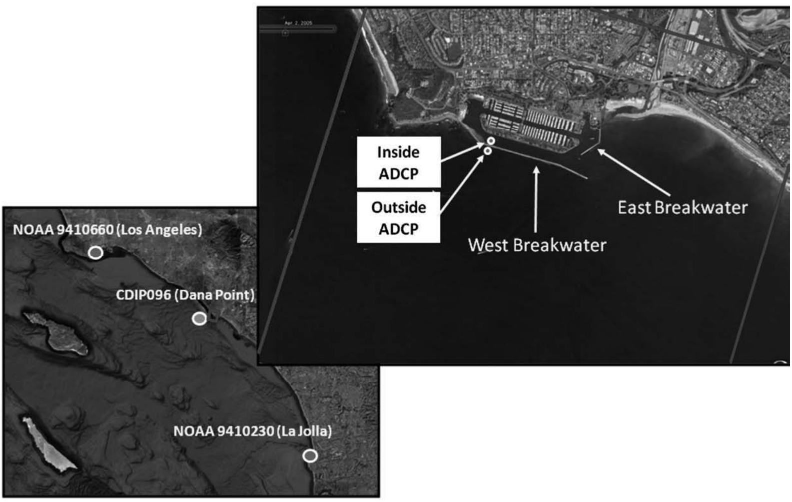

Fig. 1. Dana Point Harbor and the surrounding area. The red line denotes the CMS domain.

A field data collection program was designed for this study. A hydrographic multi-beam survey for the underwater portion along with the above-water mapping via the LiDAR scanning technology for the breakwaters was conducted in October 2009 (Fugro West 2010). Bathymetric data were also collected in the marina basins, harbor entrance and nearshore areas outside the harbor. Two ADCPs were

deployed from November 2009 through January 2010 to collect current and water level inside (without wave data collection) and outside (with wave data collection) the West Breakwater (Figure 1). Because of the instrument failure, only initial six days of data were recovered from the outside ADCP. In the last 20 years, Orange County has conducted three maintenance dredges to remove fine sand material that moved through and deposited on the harbor side of the West Breakwater. The dredged volumes inside the West Breakwater are approximately 25,000 cy in 1990, 35,500 cy in 1999, and 54,000 cy in 2009 (County of Orange 1990; 1999; 2009).

Besides the harbor bathymetry, ADCP, and dredging information, the offshore bathymetry data were extracted from GEOphysical DAta System (GEODAS) database (NGDC 2009), and waves, water surface elevation, and wind data around Dana Point Harbor were assembled for the numerical model.

Wave data were furbished by the Coastal Data Information Program (CDIP), operated by Scripps Institution of Oceanography (http://cdip.ucsd.edu/). Directional wave spectra were retrieved from the Dana Point Buoy CDIP096 in the 3-hour interval and transformed to the model seaward boundary. Figure 2 shows the 2008 wave rose for CDIP096. It is noted that the predominant waves are from the south-southwest (180-200 deg azimuth) in the summer and the west-northwest (270-280 deg azimuth) directions during the winter months. Extreme large waves are rare as more than 98 percent of the wave population shows a height less than 2 m. The annual average wave height and peak wave period are 0.95 m and 13.7 sec, respectively.

Water surface elevation data were obtained from NOAA tide gage 9410660 (Los Angeles, CA), http://tidesandcurrents.noaa.gov (Figure 1). Figure 3 shows the hourly water surface elevation relative to mean sea level from 18 November to 17 December 2009 and indicates a mixed, predominately semi-diurnal tidal regime surrounding the study area. The mean tidal range (mean high water – mean low water) is 1.16 m and the maximum tidal range (mean higher high water - mean lower low water) is 1.67 m.

Wind data were available from NOAA coastal stations at Los Angeles Pier S, CA (9410692) and La Jolla, CA (9410230), and also from the offshore NDBC Buoy 46047, http://www.ndbc.noaa.gov. Local wind observations at Dana Point Harbor (SDDPT) were provided by San Diego Weather Forecast Office, National Weather Service. Figure 4 shows time series of wind speed and direction at La Jolla, Dana Point, and Buoy 46047 for 18 to 27 November 2009. Comparing to the wind data at the coastal stations, the offshore wind is much stronger. While the wind direction at La Jolla is characterized by the diurnal cycle of the sea breeze signal, the wind at the Dana Point Station does not show a clear pattern due to sheltering effect of the local steep sea cliffs.

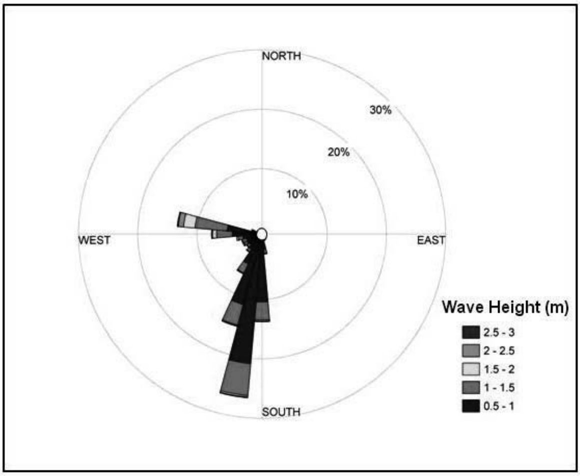

Fig. 2. Wave rose at CDIP096 for 2008.

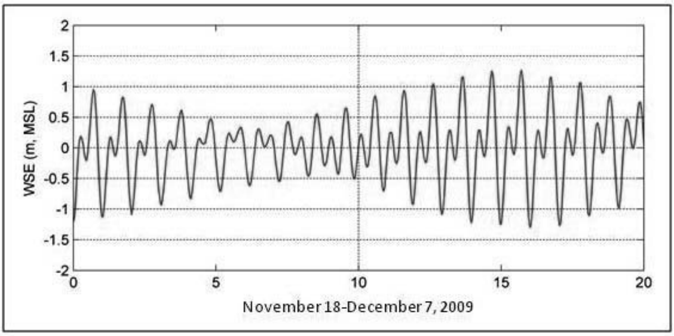

Fig. 3. Water surface elevation (WSE, m) at NOAA Los Angeles tide gage (9410660), 18 November-7 December, 2009.

The harbor and offshore bathymetry data were interpolated to configure the numerical model grid. Waves, water surface elevation, and wind data were assembled to provide forcing terms to the CMS. The ADCP measurements and dredging information were analyzed to evaluate the model performance.

Methodology

The CMS is a suite of PC-based numerical hydrodynamic, wave, and sediment transport models consisting of CMS-Flow, CMS-Wave, and CMS-PTM, http://cirp.usace.army.mil/wiki/CMS. Physical processes calculated by CMS-Flow are circulation, sediment transport, and morphology change (Buttolph et al. 2006). CMS-Wave is a two-dimensional wave spectral transformation model that

contains approximations for wave diffraction, reflection, wave transmission, wave run-up, and wave-current interaction (Lin et al. 2008). CMS-PTM is a Particle Tracking Model capable of computing the fate and pathways of sediment and other waterborne particles in the CMS-generated flow field.

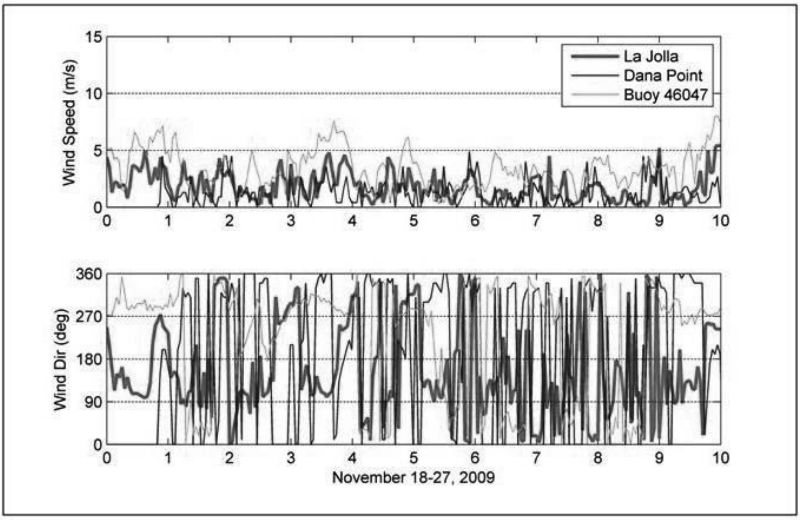

Fig. 4. Wind speed and direction at NOAA La Jolla gage (9410230), Dana Point Harbor, and NDBC buoy 46047, 18-27 November, 2009.

Figure 5 shows the CMS rectangular grid domain that consists of 399 × 327 cells surrounding Dana Point Harbor. The water depth ranges from 0 m at Baby Beach to 9 m at the harbor entrance channel inside the marina and increases to more than 10 m outside the West Breakwater. The offshore area further deepens to a few hundred meters and is open to the Pacific Ocean. A variable-resolution grid system was created to discretize the entire harbor and the offshore region, which permits much finer grid resolution (5 m) in areas of high interest such as the harbor and the breakwaters. The model domain extends approximately 5 km alongshore and 4 km offshore, and the offshore boundary of the domain reaches to the 300 m isobath.

In the CMS, both the West and East Breakwaters were specified as permeable structures, through which wave transmission, flow and sediment seepage were implemented. Based on various data sets, d'Angremond et al. (1996) examined wave transmission through permeable breakwaters and proposed the following formula for the calculation of the transmission coefficient,

$$K_t = 0.64\left(\frac{B}{H_{si}}\right)^{-0.31}\left[1-\exp\left(-\frac{\xi}{2}\right)\right]-0.4\frac{h_c}{H_{si}}, \quad (1)$$

where B is the crest width, h_c is the crest freeboard, H_{si} is the significant wave height (Figure 6), and ξ is the Iribarren parameter defined as the fore-slope of the breakwater divided by the square-root of the incident wave steepness. Equation (1) is applicable to both monochromatic and random wave in CMS-Wave (Lin et al. 2009).

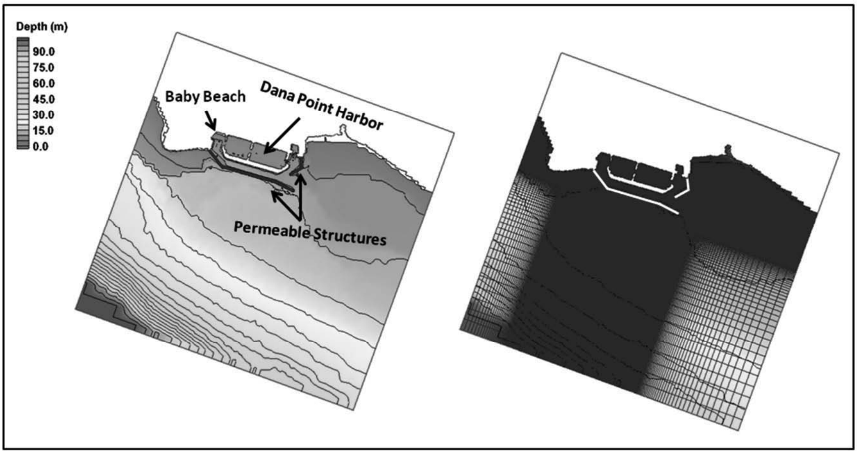

Fig. 5. The CMS model domain and configuration.

Based on the Forchheimer equation (1901), unidirectional flow, u, through porous structures is represented in the x-direction, the momentum equation as

$$g(h+\eta)\frac{\partial(h+\eta)}{\partial x} = ag(h+\eta)u + bg(h+\eta)u^2 \quad (2)$$

where g is the gravitational acceleration, h is the still water depth, η is the water surface elevation, x is the x-coordinate, a and b are the dimensional coefficients (Figure 6). The left hand side of Equation (2) is the hydraulic gradient, and the linear term on the right hand side corresponds to the laminar and the non-linear term to the turbulent component of flow resistance.

The implementation of permeable structures in the CMS requires modifications of the conservation of mass equation by introducing the structure void space, n. The revised equation is:

$$\frac{\partial \eta}{\partial t} = \frac{1}{n}\left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y}\right). \tag{3}$$

where q_x and q_y are the mass fluxes in the x and y directions. In the morphology simulation, the similar equation for the change in bed elevation is revised to account for the structure void space:

$$\frac{\partial \zeta}{\partial t} = \frac{1}{n}\left(\frac{\partial q_{sx}}{\partial x} + \frac{\partial q_{sy}}{\partial y} - E + D\right) \tag{4}$$

where ζ is the bed elevation, and q_{sx} and q_{sy} are the bedload fluxes in the x and y directions, E is the erosion flux and D is the deposition flux.

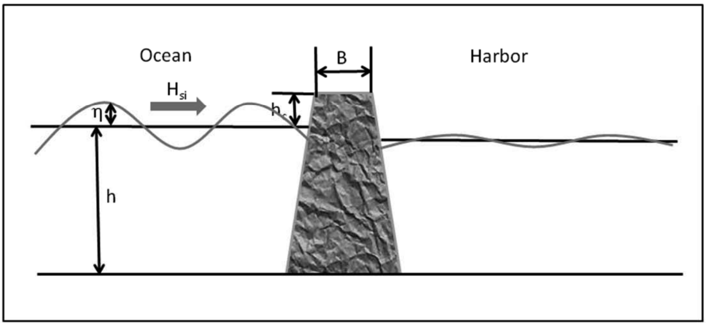

Fig. 6. Sketch of wave transmission and flow penetration through porous structure.

The implementation of the Forchheimer equation in CMS-Flow was validated by Reed (2010). The CMS-Flow output was compared to results of analytical solutions for steady flow cases. By selecting a range of resistance coefficients, *a* and *b*, for linear and nonlinear terms in the equation (Ward 1964; Kadlec and Knight 1996; Sidiropoulou et al. 2007), a sensitivity analysis was also conducted to determine the response of the CMS simulations to uncertainty of the resistance coefficients. Corresponding to different riprap sizes and a constant void space parameter, the sensitivity tests indicate that the simulated flow rates varied from 30% to 50%.

Results and discussion

The CMS simulations were conducted for a 10-day period from 18 to 27 November, 2009, which covers the beginning stage of the inside ADCP survey and the entire record of the outside ADCP survey. The calculated wave

parameters are compared with the measurements at the outside ADCP station (Figure 7). The mean significant wave height is 0.75 m. Wave heights for the 10-day period are mostly less than 1.0 m. The mean wave period is 13.5 sec, and the predominant wave direction is west-southwest. Comparing to the 2008 annual data, the 6-day period represents a slightly lower wave height and a typical wave direction in November. The wave transformation results show a good consistency with the measured wave parameters. An underestimate of wave height in the first couple of days could be related to the wind forcing since the wind data used were obtained from a different buoy.

Figure 8 shows the comparison of calculated and measured WSEs at the outside ADCP station from 18 to 27 November 2009. During this neap tidal period (Figure 3), the CMS results well reproduce the tidal signals displayed in the 6-day WSE survey outside of the West Breakwater.

The current measurements show different flow patterns at the inside and outside ADCP stations during this simulation period. The depth averaged current has a small speed of less than 2 cm/s but shows a clear flood and ebb tidal current signal along the breakwater at the inside ADCP station. The current speed at the outside ADCP station has a magnitude of about 4-5 cm/s and the dominant current directions are from west northwest (i.e., traveling along the west breakwater). Figure 9 compares the calculated current with the measurements at both inside and outside ADCP locations. In the first 2-3 days, the calculated results show that the harbor area experienced a few short periods of relatively high currents. By checking all the forcing terms in the model, the spring tide is probably responsible for those speed spikes inside and outside of the harbor (Figure 8). Similar to the ADCP data, the calculated current directions at the inside station are basically corresponding to the flood (260-300°) and ebb tide (80-120°) although the CMS results show some discrepancies at a few occasions. It is a wave-controlled environment outside the West Breakwater. Both the measured and the calculated flow directions reveal that the currents move predominantly east-southeastward parallel to the breakwater.

Sensitivity tests were conducted to examine the CMS performance. It was found that the current directions are sensitive to wind forcing and to the specifications of the structure porosity (selection of the resistance coefficients in the Forchheimer equation) because of the weak current inside the harbor. Sheltered by breakwaters, current speeds inside the harbor are not sensitive to wind but current directions do response to changes in wind. Using the buoy and the Dana Point wind, calculated current speeds are overestimated and current directions consistently show east-southeastward flow outside the harbor. The simulation with the La Jolla wind produces the better model and data comparison at the two ADCP stations (Figures

9 and 10). Apparently, local wind measurements on the ADCP site are necessary to provide the best wind forcing for the model.

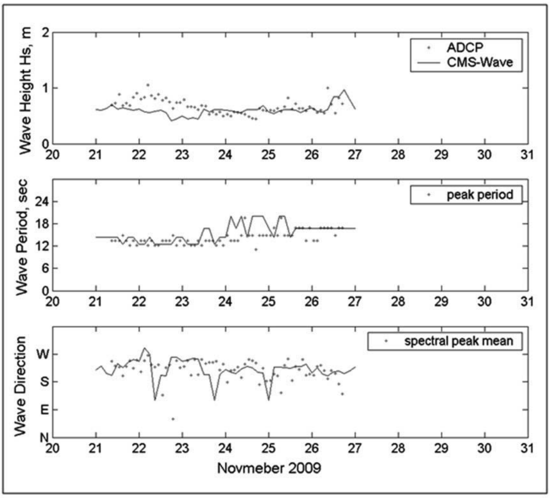

Fig. 7. Comparisons of wave parameters between the calculations and the measurements at the outside ADCP station.

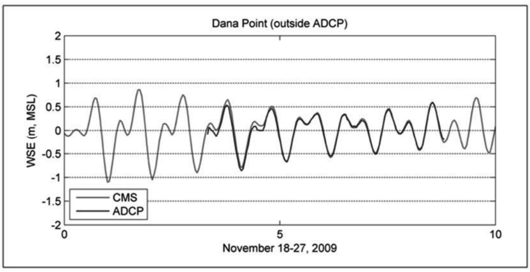

Fig. 8. Comparisons of water surface elevations between the calculations and the measurements at the outside ADCP station.

A previous circulation study at Dana Point Harbor (SAIC 2003) showed the evidence of flows through the West Breakwater and impact of the through-flow on the current changes inside the harbor. The entire West and East Breakwaters were specified as permeable for the CMS calibration. As a sensitivity test, the West Breakwater was specified as partially permeable. Corresponding to those specifications, the model and data comparisons at the two ADCPs are shown in Figure 11. As the length of the permeable portion of the breakwater increases and more water penetrates through the structure, the calculated current speed increases and the current direction changes at the inside ADCP station.

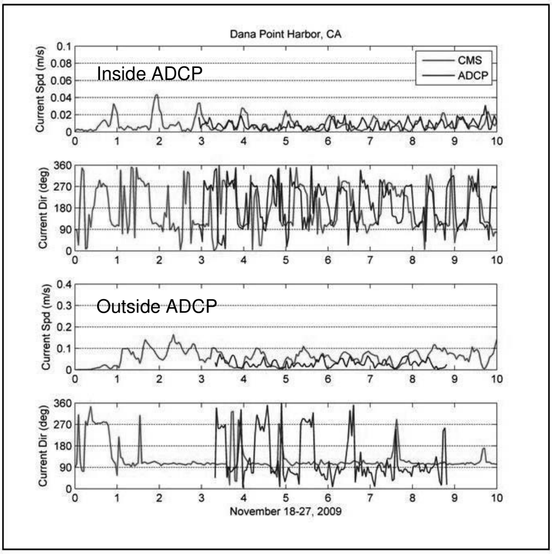

Fig. 9. Comparisons of currents between the calculations and the measurements at the inside and outside ADCP stations.

The Google Earth photograph taken in 2005 (Figure 1) shows sand penetration through and sand accumulation inside the West Breakwater before the 2009 harbor maintenance dredge. Based on this latest dredging information, average annual sediment transport rate is around 5,000-6,000 cy. To estimate the sediment seepage through the permeable structure, the transport module in the CMS was set up. The structure permeability was specified by testing and adjusting the resistance parameters in the Forchheimer equation and the structure void space in the conservation of mass equation. Figure 12 shows the morphology change surrounding the west portion of the West Breakwater at the end of the 10-day simulation. Although small, sand accretion can be detected inside the harbor and the distribution pattern of the bed change looks similar to the Google Earth photograph shown in Figure 1. Transport within a structure cell is greatly reduced by the weaker flow speed, lower wave energy, and subsequent smaller bottom stresses. As a result, large deposition occurs within the breakwater. To estimate total sediment volume changes related to the sediment seepage through the breakwater, a polygon area is drawn by the breakwater inside the harbor on Figure 12. The morphology and bed volume changes within the area were estimated at the end of the simulation. Time extrapolation of the CMS results presented an approximate sediment transport rate of 4,000 cy annually through the West Breakwater, which is quantitatively comparable to the average annual volumes dredged inside of the West Breakwater.

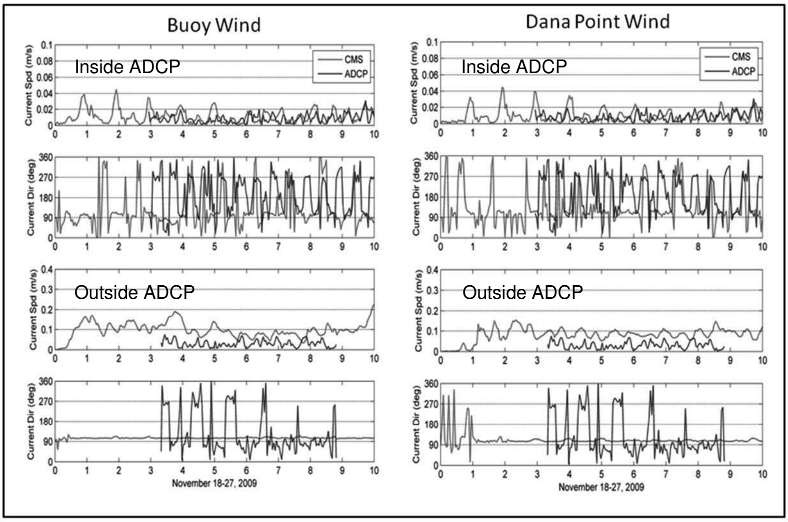

Fig. 10. Comparisons of currents between the calculations and the measurements at the inside and outside ADCP stations. The CMS was driven by the offshore and the Dana Point wind, respectively.

Conclusions

Wave transmission and flow penetration through a permeable breakwater were incorporated into the CMS, a coupled wave, flow and sediment transport numerical modeling system. The model performance was validated by the measured waves, current, and water surface elevation. The implementation of the algorithms for flow and sediment seepage through the permeable breakwater was verified by the historical dredging information.

The CMS results indicate that it is a tide-dominated environment inside and a wave-dominated environment outside the West Breakwater at Dana Point Harbor. During the 10-day simulation (corresponding to a neap tide) for 18 to 27 November, 2009, the depth average current has a speed of 2-10 cm/s. Sensitivity tests reveal that the flow variations inside the harbor are closely associated with the wind forcing and the specifications of the porous structure.

By applying and adjusting the parameters of the breakwater porosity and flow resistance, sediment transport through the permeable structure was estimated. The sediment transport rate obtained from the CMS simulations was validated via the volumes from the historical maintenance dredging activities at Dana Point Harbor.

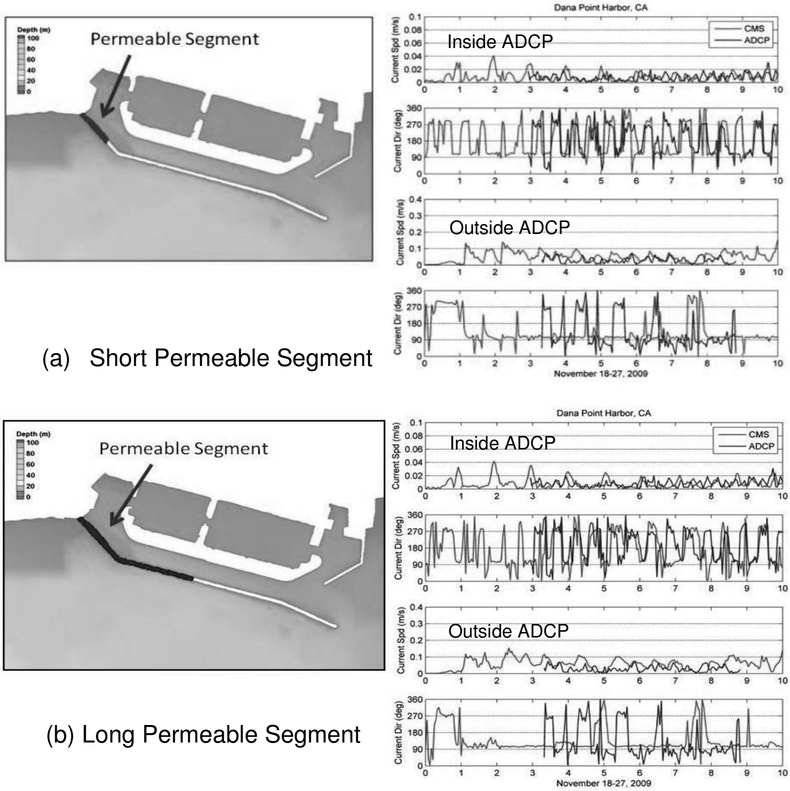

Fig. 11. Comparisons of currents between the calculations and the measurements at the inside and outside ADCP stations. Different lengths were specified for the permeable portion of breakwaters.

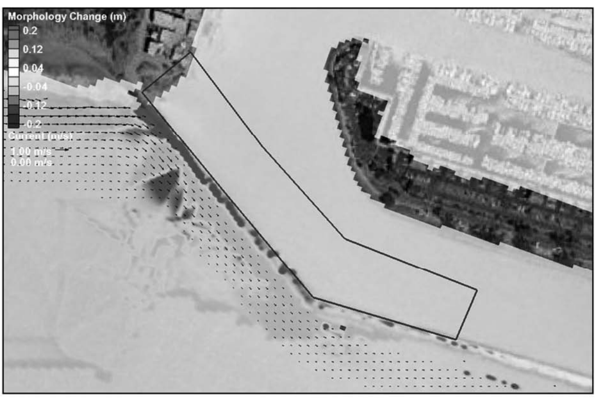

Fig. 12. Morphology change at the end of the 10-day simulation. The blue line denotes the area where bed volume change was estimated.

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